# HIGH PERFORMANCE PLASMAS ON THE NATIONAL SPHERICAL TORUS EXPERIMENT


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## *Abstract*

The National Spherical Torus Experiment has produced toroidal plasmas at low aspect ratio ($A$ = $R/a$ = 0.86m/0.68m ~ 1.3, where $R$ is the major radius and $a$ is the minor radius of the torus) with plasma currents of 1.4MA. The rapid development of the machine has led to very exciting physics results during the first full year of physics operation. Pulse lengths in excess of 0.5s have been obtained with inductive current drive. Up to 4MW of High Harmonic Fast Wave (HHFW) heating power has been applied with 6MW planned. Using only 2MW of HHFW heating power clear evidence of electron heating is seen with HHFW, as observed by the multi point Thomson scattering diagnostic. A non-inductive current drive concept known as Coaxial Helicity Injection (CHI) has driven 260kA of toroidal current. Neutral beam heating power of 5MW has been injected. Plasmas with $\beta_t$ ($=2\mu_0\langle p\rangle/B^2$ = a measure of magnetic confinement efficiency) of 22% have been achieved, as calculated using the EFIT equilibrium reconstruction code. $\beta$ limiting phenomena have been observed, and the maximum $\beta_t$ scales with $I_p/aB_t$. High frequency (>MHz) magnetic fluctuations have been observed. H-mode plasmas are observed with confinement times of > 100ms. Beam heated plasmas show energy confinement times in excess of those predicted by empirical scaling expressions. Ion temperatures in excess of 2.0keV have been measured, and power balance suggests that the power loss from the ions to the electrons may exceed the calculated classical input power to the ions.


## I. INTRODUCTION

The National Spherical Torus Experiment (NSTX) [1] is a midsize toroidal magnetic confinement device that is designed to produce plasmas with a low aspect ratio. The spherical torus has been predicted to have many attractive features including high normalized pressure or $\beta_t$ ($= 2\mu_0\langle p\rangle/B_t^2$) [2] and improved stability against small scale fluctuations [3] which are believed to degrade confinement. The spherical torus has been the focus of increased experimental activity following the experimental demonstration of high $\beta$ [4] with good confinement [5] on the pioneering START [6] device.

An assembly drawing of NSTX is shown in Figure 1. The extreme geometry is apparent from the drawing. The column (in red) in the center of the device provides the toroidal field and is capable of carrying a net vertical current in excess of 2.5MA (corresponding to the


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maximum toroidal field on axis of 0.6T). The major design parameters of the NSTX device are shown in Table 1.

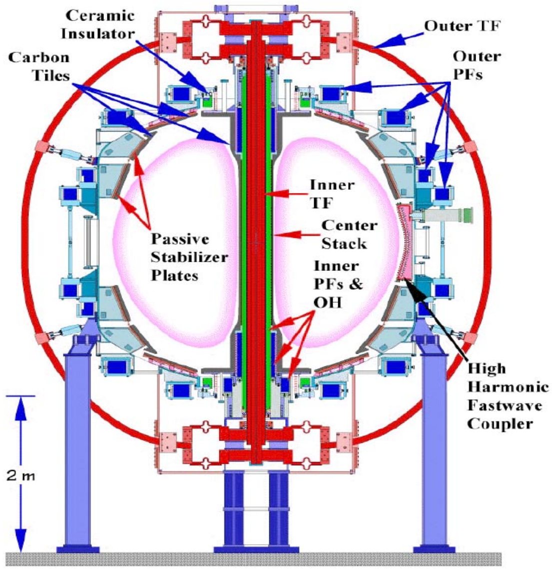


**Figure 1.** Cross-section assembly drawing of NSTX

**Table 1.** Device parameters for NSTX

| Parameter | Achieved | Planned |
|---|---|---|
| Plasma current ($I_p$) | 1.4 MA | 1.0 MA |
| Toroidal field ($B_t$) | 0.6 T | 0.6 T |
| Major radius (R) | 86cm | 86cm |
| Minor radius (a) | 68cm | 68cm |
| Neutral beam power ($P_{NBI}$) | 5MW | 5MW |
| Radio heating power ($P_{RF}$) | 4MW | 6MW |
| Elongation ($\kappa$) | 2.4 | 2.2 |
| Pulse Length | 0.5s | ~5 s |

The primary benefit of low aspect ratio is the increased field line length on the inboard (small major radius) side of the device. This is beneficial since the curvature of the field lines in this region is in the direction which is stabilizing for several classes of plasma instabilities. This is primarily a geometric effect.

Along with this benefit comes an important issue that must be addressed: the small area on the interior of the plasma. This geometric limitation creates difficulty for current drive, which is achieved in conventional tokamaks by a solenoid transformer, and makes the use of super-conducting toroidal field coils hard to envision. The limited area for this transformer on an ST creates a constraint on the achievable transformer-driven pulse length for an ST. Much of the research program for NSTX is aimed at alleviating this constraint.

## II. CO-AXIAL HELICITY INJECTION

Coaxial Helicity Injection [7] is a current drive technique that uses an externally applied DC voltage to initiate a toroidal plasma current. This technique was first used to effect on the HIT device [8]. Poloidal current is drawn between the outer portion of the vacuum vessel and the center stack, which are electrically isolated from each other by two insulators, one at the top of the center stack and one at the bottom. In order to encourage current to flow along the desired path, the poloidal field is maximized across the bottom insulator, where the $J_\theta x B_t$ force points up into the vessel, and minimized across the top insulator. Current cannot flow purely in the poloidal direction however, due to the applied toroidal field. Current instead flows along the nearly helical resultant field lines, causing the current to make several toroidal transits before contacting the opposing electrode.

In this manner a poloidal current is used to create a toroidal current. To date a toroidal current of 260kA has been driven using only ~25kA of injected poloidal current, as can be seen in Figure 2. This large multiplication ratio is the result of the high ratio of the toroidal field and the poloidal field in the lower insulator region.

This technique has not yet been used in conjunction with auxiliary heating due difficulties in obtaining desirable equilibria. The difficulties are associated with insulator design issues and poloidal field control in the upper electrode.

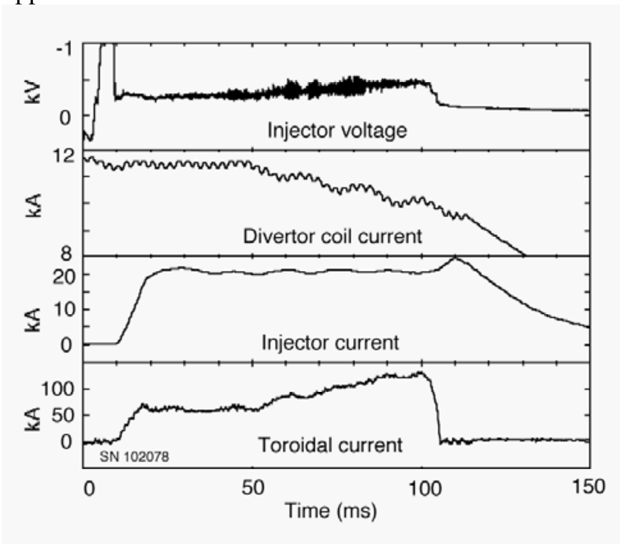


**Figure 2 Current and voltage traces from a CHI discharge on NSTX**

## III. HIGH HARMONIC FAST WAVE HEATING

The NSTX high harmonic fast wave antenna consists of 12 straps which are powered by six independent RF sources. The antenna is large, occupying approximately 1/3 of the circumference of the device at the outboard mid-plane. The large antenna helps reduce peak power density to values of ~2MW/m$^2$ which has led to reliable operation without the large density increases often associated with high power RF heating. The low power density also reduces antenna conditioning time.

A radio frequency wave heating scheme known as high harmonic fast wave heating [9] has been used to

effectively heat electrons on NSTX. Peak temperatures of 1.8keV have been obtained for parallel wave numbers between $7m^{-1}$ and $14m^{-1}$. Shown in Figure 3 are 2 shots one with RF heating and one without, showing significant electron heating. To date, no parasitic ion heating caused by coupling to the ion Bernstein wave has been observed, which was an early theoretical concern for $T_i(0)$ > 1keV.

The phase of each antenna strap can be independently controlled in real time to vary the launched wave spectrum between a slow (heating) and a fast (current drive) phasing. Long range uses for this ability include current and pressure profile control. Such control could allow more reliable operation near $\beta$ limits.

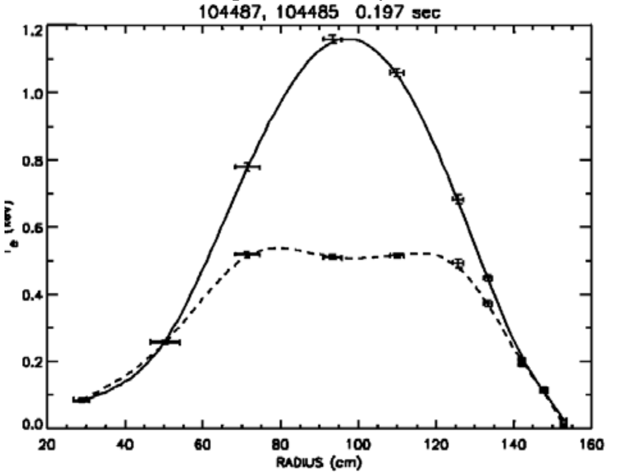


**Figure 3** Two comparison discharges, one with 2MW of RF heating one without, showing strong RF heating

## IV. NEUTRAL BEAM HEATED DISCHARGES

### A. *High plasma current*

Another benefit of low aspect ratio is that the toroidal plasma current can be much higher for a given applied axial toroidal magnetic field. The maximum plasma current attained to date is 1.4MA with a 4.0kG toroidal field. An important part of this result was the small inferred halo currents, which are induced py plasma disruptions and which have been observed to cause significant damage to conventional tokamaks at high plasma current. The ability to support high plasma current is important, since toroidal burning plasmas require a minimum poloidal magnetic field in order to contain $\alpha$-particles from D-T fusion reactions.

### B. *Extended Pulse*

Initial experiments aimed at extending the pulse of NSTX discharges and have successfully extended the total pulse length of 1MA discharges to > 0.5s. The techniques used to date include neutral beam preheat during the current ramp and raising the toroidal field to control MHD activity. Evidence suggests that the pulse length limit on NSTX is set by the central safety factor, *q(0),* being of order unity.

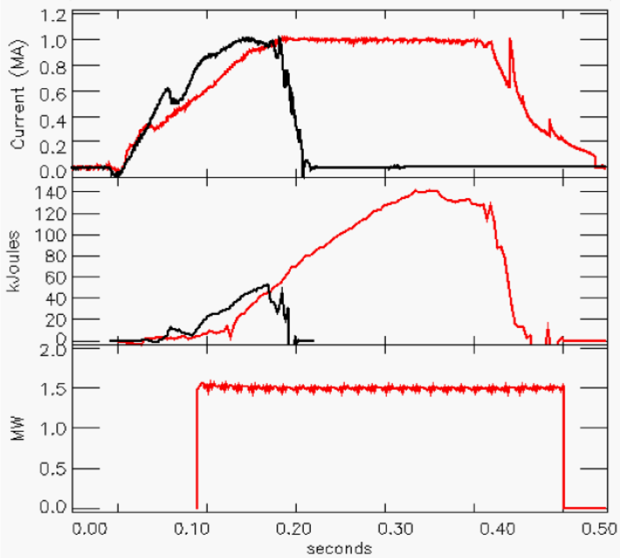


**Figure 4** Comparison of a a) plasma current b) stored energy and c) neutral beam power for a 3kG ohmic discharge (101522) and a 4.5kG discharge with neutral beam preheat (103887)

### C. *High Normalized Pressure*

Neutral beam heating with injected power reaching 5MW has been used on NSTX to raise the plasma pressure to a substantial fraction of the predicted limit.

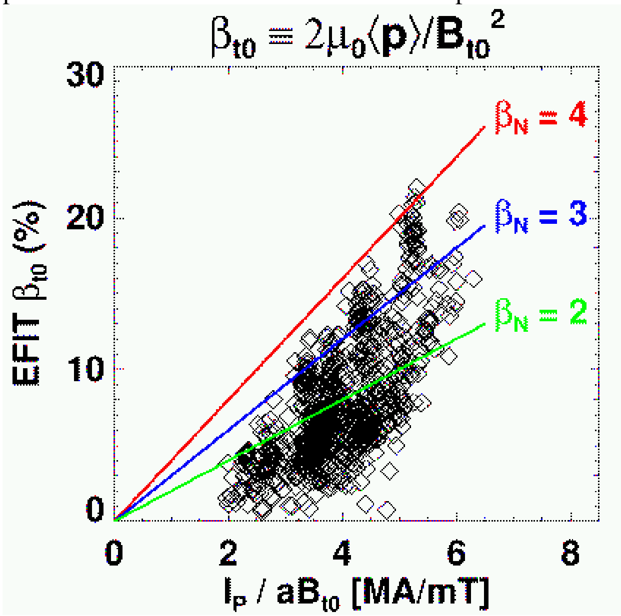


**Figure 5** $\beta_t$ vs. $I_N$ for NSTX plasmas with strong neutral beam heating

Plasmas with $\beta_t$ ~ 20% have been achieved on NSTX Shown in Figure 5 is $\beta_t$ plotted as a function of the normalized plasma current $I_N = I_p/aB_t$ (MA/m·T). Ideal (non-resistive) magneto-hydrodynamic (MHD) modes are predicted to limit $\beta_t$ to a value that scales linearly with $I_N$ [10]. The observed nearly linear scaling of $\beta_t$ with $I_N$ indicates that the observed limit may be set by ideal MHD instabilities.

### *D. High Confinement*

The global energy confinement time on NSTX has been measured and compared to conventional tokamak scaling relations. Shown in Figure 6 is the energy confinement time as determined by magnetic analysis using the EFIT code [11] plotted against two conventional tokamak scaling relations, ITER89P and ITER98y2, which were originally developed for the ITER project [12]. NSTX confinement times typically exceed the more pessimistic ITER89P by a factor of two. The confinement times exceed the H-mode (High confinement mode) confinement scaling by a factor of up to 1.4, even though the bulk of the discharges in the plot

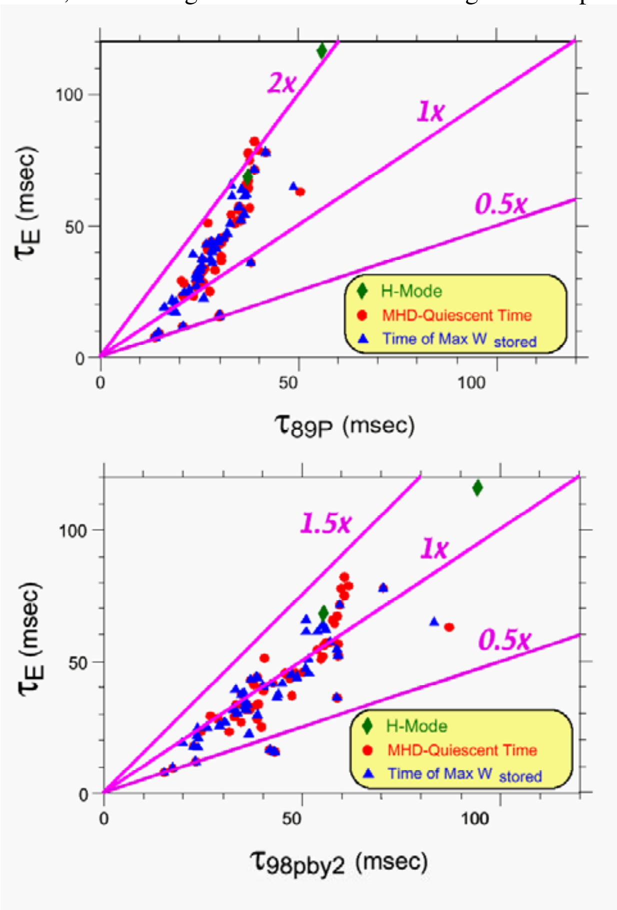


**Figure 6** Scatter plots of measured energy confinement times plotted versus the a) ITER89P and b) ITER98y2 scaling relations

were limited discharges and were not in H-mode. The enhanced confinement time is an important result for the spherical torus.

### *E. H-Mode*

The highest confinement times achieved to date have occurred when the plasma was in H-mode. Confinement times in excess of 100ms have been achieved with plasma currents of 800kA. The H-mode discharge are characterized by a sudden drop in the measured deuterium-$\alpha$ emissions simultaneous with an acceleration of the density increase.

The H-mode is a relatively new phenomenon on NSTX and has not yet been fully exploited due to issues with reproducibility, probably associated with divertor tile conditioning. Operation in H-mode holds promise for further improvements in plasma performance.

## V. PROFILES AND POWER BALANCE ISSUES

Measured profiles of density and temperature for a high performance neutral beam heated discharge from NSTX are shown in Figure 7. The electron temperature and density were measured with a multi-point multi-pulse Thomson scattering diagnostic which measures the Doppler broadening of laser light classically scattered off electrons. The ion temperature was measured using charge exchange recombination spectroscopy (CHERS) which measures the Doppler broadening of a carbon VI charge exchange emission line. CHERS requires that at least one neutral beam source be on to act as a source of charge exchange electrons. The ion temperatures have

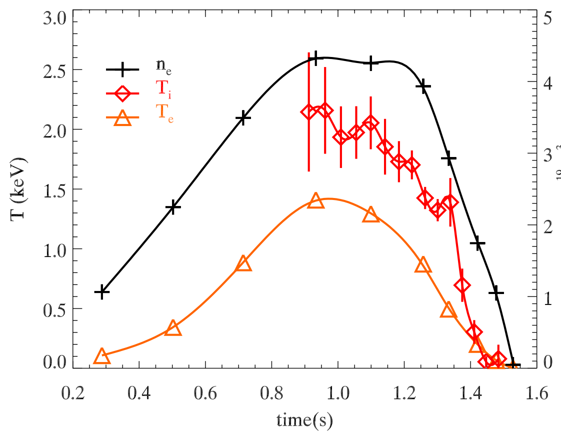


**Figure 7** Electron temperature, electron density, and ion temperature profiles for high performance shot 104001.

been independently confirmed with neutral particle analyzer measurements, and the electron temperature measurements are consistent with flux consumption calculations made using a neoclassical resistivity model [13]. The electron density measurements have been confirmed against both reflectometry and interferometry.

These profiles have been used to calculate the classical collisional power balance for NSTX. The calculation was done using the TRANSP code, which is a standard analysis tool developed for use on conventional tokamaks. The results of this calculation are shown in Figure 8. The curious result is that ion difference power, which is the remainder of the ion power flow after neutral beam ion heating, transient effects, and electron-ion collisional coupling are taken into account is large and positive. This implies two important points: a) that there is a possible anomalous ion heating mechanism, and b) that the ion confinement is very good.

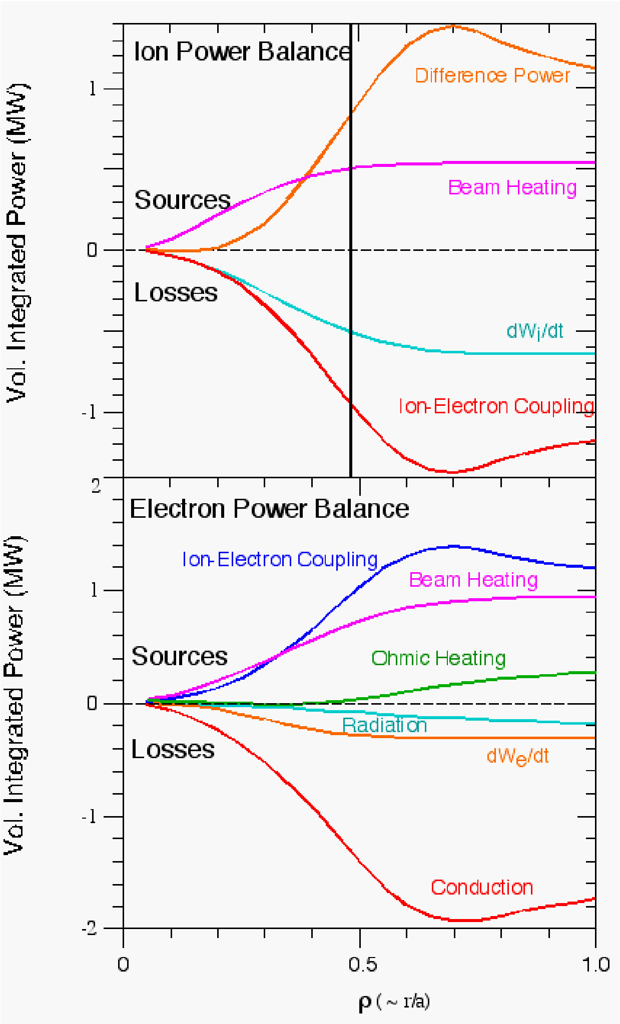


**Figure 8** Power balance profiles for shot 104001. Each point on each trace represents the integral of the power flow for each mechanism within the enclosed volume.

A mechanism has been proposed [14] whereby a fast particle driven Alfvén instability, called the compressional Alfvén eigen-mode (CAE), could heat thermal ions. The power flow is from the fast particles to the waves and from the waves to the bulk ions. This mode has been tentatively identified on NSTX [15]. The vertical line in the figure is the theoretically predicted location of the peak CAE mode amplitude. The correlation between the off axis maximum in the derivative of the ion-electron coupling is intriguing, but further work is required to make a firm correlation between the presence of CAE modes and any anomalous ion heating mechanism that may be identified on NSTX.

## VI. SUMMARY

High performance discharges have been created on NSTX using strong auxiliary heating, both by HHFW and by neutral beams. $\beta_t$ ~20% has been achieved using neutral beam heating. The maximum achievable $\beta_t$ scales with normalized current. Ion temperatures of 2.0keV have been measured during beam heating. H-mode has been observed on NSTX and energy confinement times in excess 100ms have been measured. High harmonic fast wave heating has been effectively used to heat electrons to 1.8keV, with no apparent density rise and without heating ions. Coaxial Helicity Injection has been used to drive up to 260kA of toroidal current. Energy confinement times have been measured and exceed ITER98pby2 scaling by a factor of 1.4. Power balance calculations made using the measured kinetic profiles indicate that the power loss from the ions to the electrons exceeds the calculated classical input power to the ions. Compressional Alfvén eigenmodes have been observed on NSTX and are a potential candidate to explain the inferred anomalous ion heating.

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